Sep 17th, 12:00 AM - Sep 19th, 12:00 AM

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IUTAM Symposium Architectured Material Mechanics,
T. Siegmund, F. Barthelat, eds
September 17-19, 2018, Chicago, IL, USA, , Chicago, IL, USA

Analysis of plant-inspired, osmosis-mediated structures

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KEYWORDS:
Closed-cell, poroelasticity, osmotically active

The plant kingdom quietly goes about life without the presence of muscles. Water flow, both within and outside the plant cells, is the major driving force for movement in flora [1]. Deformation has been modelled using classic poroelasticity, which assumes flow of water through an open, porous network. However, in closed cell composites, water transport is driven via osmosis through a solid membrane (cell walls) rather than flowing freely through open pores. Darcy's law based poroelasticity does not physically describe this behaviour. To account for the physical process within the closed cell structures as opposed to porous flows, we fabricate and characterize closed-cell, fluid-filled soft material composites. Through this study, we aim to describe coupled water transport/mechanical deformation in plants and other similar biological structures. The synthetic plant tissue analogue developed in this project may also drive development of energy efficient soft robotics and osmotically-tuneable, implantable active materials.

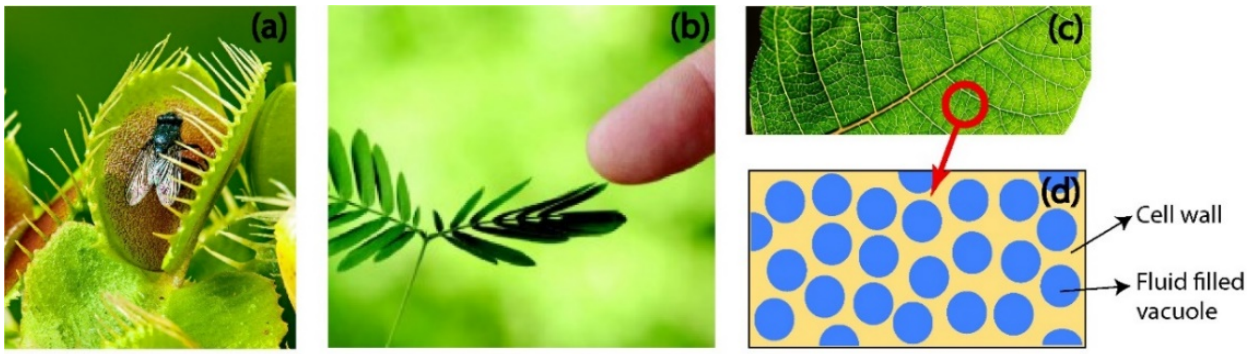

Figure 1. (a) Venus fly trap, captures insects by closing its lobes; (b) Mimosa curls its leaves inwards upon being touched;
(c) & (d) Schematic, simplified microstructure of a plant tissue
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A challenging element of this study is the fabrication of hyperelastic and osmotically active closed cell foam materials. Templating techniques require extraction of the template, which is impossible for a closed cell, and top down manufacturing at this length scale is either currently infeasible (e.g., additive manufacturing) or must address issues with achieving precise encapsulation of the osmolyte (e.g., soft lithography). We report on a bottom-up sample fabrication technique in which PDMS (Sylgard 184) is used as the stretchable, semi-permeable membrane material confining the osmotic solution – salt water. A high internal phase emulsion is prepared with brine solution as the internal phase and Sylgard 184 as the continuous phase. The large difference in viscosity of the two phases, makes conventional emulsification techniques intractable for achieving low

polydispersity mixtures. Consequently, a coarse emulsion is prepared by gently mixing the two phases together. This mixture is then passed through a high throughput microfluidic chip [2] consisting of an array of pillars which facilitates the formation of micro droplets of internal phase by interrupting the flow of the coarser emulsion. The refined emulsion thus formed is cured to obtain the desired closed-cell, fluid-filled composite.

To understand the physico-chemo-hydro-mechanical behaviour of such composite foams, we carry out two mechanical tests. The equilibrium swelling characteristics of the foams are examined for varying PDMS properties under free and geometrically constrained conditions. The fluid-solid composite systems are also tested under uniaxial loading to evaluate the effect of cell turgidity on tissue stiffness by varying the salt concentration. It is found that foam stiffness is approximately proportional to cell turgidity at high water content. This behaviour is consistent with that of plant tissues reported in scientific literature [3]. Additionally, to discern the local poroelastic behaviour, micro-indentation is performed on these foams. While the material behaves largely elastically at low loads, there is significant divergence from this behaviour at higher loads, potentially due to water transport across cells.

We report on a fabrication technique for highly uniform closed-cell, osmotically-active material geometries that mimic the behaviour of non-vascularized plant tissues. The preliminary results obtained here will help us to develop a physics-driven model of the coupled phenomena of mass-transport and deformation in soft biological tissues.

Acknowledgments

We are grateful to NSF for supporting this project. We are also thankful to Dr.Glennys Mensing for providing valuable insights about microfluidics.

References

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